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(54) Abstract Title
Improvements in, or relating to, the control of buoyancy underwater at great depths

(57) In conventional controllable buoyancy equipment, an incompressible liquid such as oil, is pumped between a pressure proof container filled with low pressure gas and an external flexible envelope. In one aspect of the present invention, the pressure-proof container is filled with gas at a pressure equivalent to the operating depth. This converts the compression stress on the container at depth to tensile loads on the surface, which are much easier to accommodate, and reduces the power needed to achieve a given rate of change of buoyancy. In a second aspect of the invention, the liquid is replaced by the pressuring gas, reducing the total weight and allowing larger ranges of buoyancy to be covered.

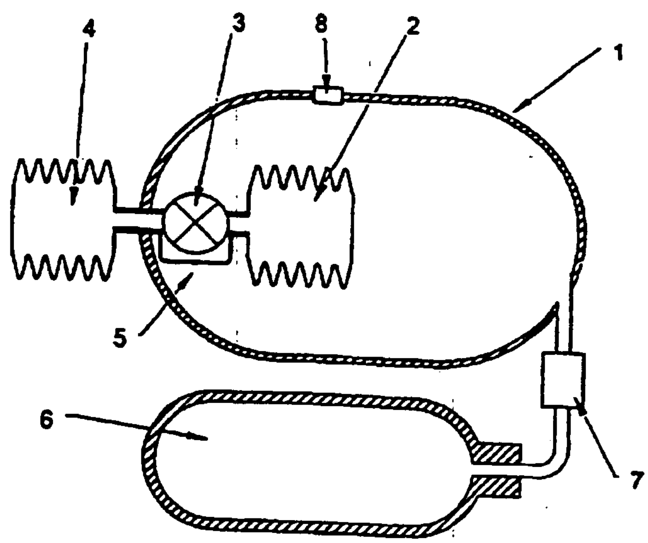

Figure 2

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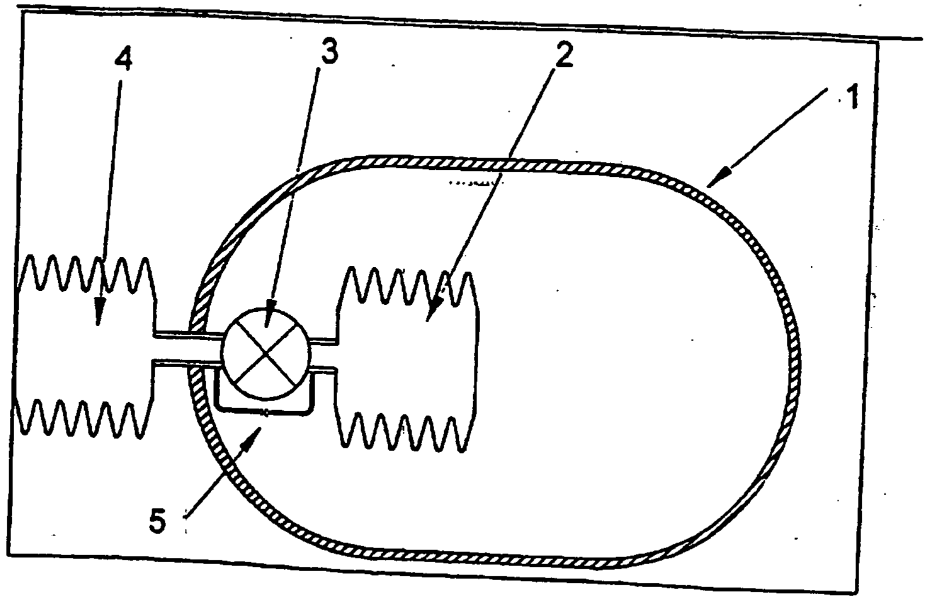
FIGURE 1



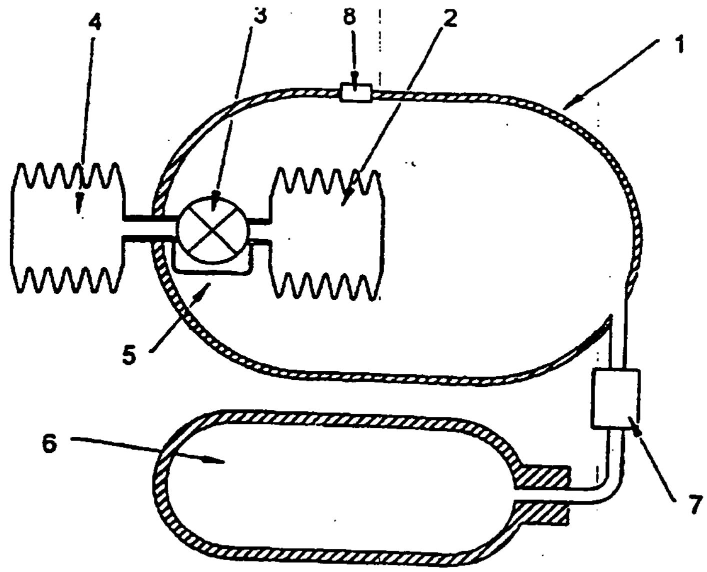
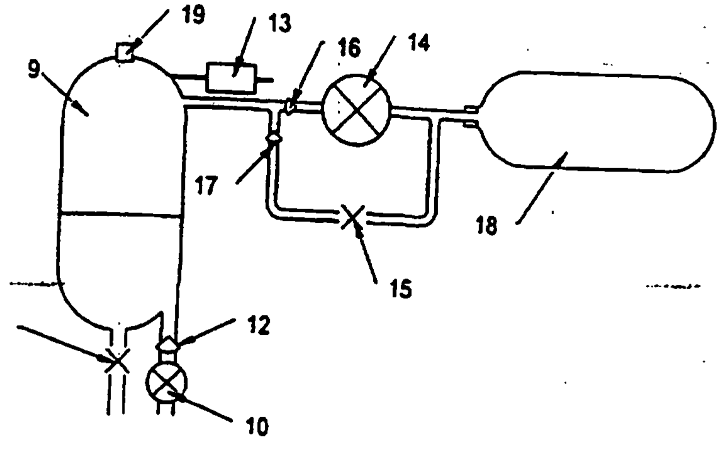


Figure 2

FIGURE 3



IMPROVEMENTS IN, OR RELATING TO, THE CONTROL OF BUOYANCY UNDERWATER AT GREAT DEPTHS.

Introduction - Technical Requirements

This invention is concerned with the control of buoyancy at depths down to at least 3km.

In the Offshore Oil Industry, it is frequently necessary to raise or lower heavy objects - as much as 30 tons - onto the sea bed: - new equipment must be installed and defective items replaced. At great depths, this work must be carried out by Remotely Operated Vehicles (ROVs), whose buoyancy can be varied only within narrow limits, as discussed below. In the absence of any method of making major changes to the buoyancy, three methods are used.

1. The ROV manoeuvres vertically using Thrusters, just as a helicopter uses its rotors. This method is clearly limited by the power available; the normal maximum is about 200kg.

2. For larger loads, a "Weight Substitution" method is used. For example, to lift a heavy item from the seabed, an ROV may be loaded with a disposable object of the same weight, extra fixed buoyancy being added to compensate. The ROV then descends, attaches itself to the object to be lifted, drops the disposable weight and returns to the surface. This method is cumbersome, time-consuming and requires a good knowledge of the weight to be lifted: the ROV must be specifically set up for each mission.

3. For very heavy objects, such as lengths of pipe, there is no alternative to lowering from the surface using cables. This method is very costly, since it requires a specialised crane barge, and the movement of the surface vessel due to wave action may make it very difficult to locate the load precisely.

A means of varying the buoyancy of an ROV, or an associated device, over wide limits would clearly simplify all these operations.

All the missions outlined in 1 - 3 above follow the same course. The ROV leaves the surface with or without a load. It then descends, at a controllable rate, to the sea bed, which is at a known depth. Once it has reached its operating depth, the device must change buoyancy as required by its mission. It may pick up one load, and carry it to another area, or place it in a basket. During this "operating" phase, the ROV will usually stay within 100m of the sea bed. Finally, when its mission is complete, the ROV will return to the surface at a controlled speed, with or without a load which may or may not be the same weight as the original.

Present ROVs are controlled, and supplied with power, through umbilical cables from the surface. These umbilicals are likely to become entangled, as well as giving a great

deal of drag, and so they should be kept to a minimum. Buoyancy control systems which require hoses, etc., from the surface are disadvantageous in this respect.

Present State of the Art

Objects underwater are usually made buoyant by attaching a flexible envelope to them, which is then inflated with gas from the surface. This method is inherently uncontrollable, since as the object rises, the pressure decreases, thus allowing the gas to expand, further increasing the buoyancy. Several methods of overcoming this defect have been proposed. One common solution is to provide the majority of the buoyancy required by "Constant Volume" lifting bags". Unlike the common "parachute" lift bags, which have an open bottom, these are totally enclosed. They are fully inflated on the seabed, so that they cannot expand further; instead, the gas is allowed to escape through an over-pressure valve. However, if the assembly is made to descend, for any reason, there is no means of replacing the lost gas, so the remaining gas is compressed, the buoyancy decreases and the whole assembly descends out of control. This defect can be overcome by providing an external supply of gas which is metered through a demand valve set to maintain the pressure within the envelope slightly above the local pressure. Thus, when the apparatus descends, the gas required to maintain buoyancy is provided by the supply; when it ascends, the excess gas is vented through an over-pressure valve as usual. Several inventors have proposed this system in various forms[(1), (2), (3)], although it is seldom used in practice.

All systems using compressed gas become more difficult as the depth increases. If the gas is supplied from the surface, the hose must be capable of carrying the volume of gas required and also of sustaining an internal pressure significantly greater than the pressure at the operating depth. The gas can also be provided by a high pressure cylinder, but at great depths, the volume of the cylinder must be comparable with that of the envelope, so the total weight of the system is increased. Cylinders might be used for a simple lift, but would need to be very large indeed if delicate buoyancy control, involving some loss of gas, is required. Furthermore, at very high pressures, common gases no longer obey the simple gas laws, and this further reduces the buoyancy that can be achieved with cylinders of compressed gas. For these reasons, gas buoyancy is seldom used at depths greater than 500m.

Conventionally, limited buoyancy control can be achieved at very great depths using a different system illustrated diagrammatically in Figure 1. This is ultimately derived from a buoyancy control system used on some early submarines in which a sealed piston in the wall of the pressure hull was moved in and out by a screw mechanism.

A rigid pod (1) capable of resisting the external pressure, such as the life-support capsule of a manned submersible, contains a flexible capsule (2) filled with oil, or a similar incompressible liquid, whose volume is significantly less than the total internal volume of the pod - the latter is filled with gas, such as air, at low pressure. To increase the buoyancy, the oil in the capsule is driven into a second capsule outside the pod by a pump, which must be capable of overcoming the pressure difference. The gas pressure in the pod falls, but the amount of water displaced by the device, and therefore the buoyancy, increases. To decrease the buoyancy, a valve bypassing the pump is opened, allowing the external pressure to drive the oil in the external capsule back into the internal capsule; the pressure within the pod increases simultaneously.

The Invention

The central feature of this invention is the provision of an internal counterpressure to oppose the ambient pressure at the operating depth. This has two main advantages. Firstly, it converts the compression stress on the Pressure-Proof Pod in Fig 1, to tension stress which is much easier to deal with and leads to lighter structures. Secondly, it reduces the pressure differential to be overcome by the pump, thereby reducing the power required to achieve a given rate of change of buoyancy. This invention, which can be applied in many ways, is illustrated by the two systems discussed below. These are provided by way of example only; the invention is not limited to these specific embodiments.

Example 1

Example 1, shown in Figure 2, is functionally equivalent to that shown in Figure 1, the only change being to raise the pressure in the "Low Pressure Pod" to approximately the ambient pressure at the operating depth. However, the Pod must be large enough to accommodate the internal capsule, and it would have to have very thick walls to withstand the maximum internal pressure on the surface. It is therefore preferable to make the pod relatively thin-walled and contain the high pressure gas in a separate tank (6). As the device descends an automatic valve (7) allows gas from this tank to enter the pod, keeping the pressure within the latter approximately equal to the external pressure. This supply is shut off when the device reaches its operating depth, and thereafter operates in the same way as that shown in Figure 1. As the device ascends at the end of its mission, the gas within the pod is allowed to escape through a conventional over-pressure valve (8).

Figure 2

In order to keep the high pressure reservoir (6) as small as possible, it is desirable to keep the dead space inside (1) to a minimum. However, as this space is reduced, the variation in pressure as the capsule (2) is inflated and deflated increases, and this increases the power requirements of the pump. All these parameters must be taken into account in optimising the design.

This system is simple and robust, and the positive-displacement pump is a significant advantage. On the other hand, the need to carry a significant amount of the working liquid, and to provide the flexible capsules can cause problems, particularly in the larger sizes. These problems can be overcome to some extent by replacing the oil with water which can be loaded in situ, and sub-dividing the capsules.

Example 2

Example 2 eliminates the oil, and replaces the flexible capsules with a fixed-volume chamber, which can be partially filled with water to change the buoyancy, like the buoyancy tanks on a conventional submarine. The main features of the system are shown in Figure 3 below.

A buoyancy chamber (9) of suitable size, is equipped with a ballast water pump (10) and a ballast dump valve (11). The chamber itself does not need to be strong or rigid - it can be made of flexible material, or glass-reinforced plastic, for example. The pump and dump valve allow the buoyancy to be varied continuously: a constant volume lift bag could only provide constant buoyancy. To decrease the buoyancy, the pump is used to drive water into the envelope against the slight pressure differential maintained by the control valve (15) and the pump (14); the operation of these is discussed in more detail below. This ballast water increases the pressure in (9) thus activating the pump (14), as described below so that the excess gas is pumped back into the reservoir (16). To increase the buoyancy, a ballast valve in the bottom of the envelope is opened, allowing the internal pressure to expel the ballast water; further gas is added from the demand valve to maintain the pressure. Back-flow through the pump (10) is prevented by a one-way valve (12). The buoyancy chamber is also provided with an over-pressure valve (19); this is largely a safety precaution and will only be used during the final ascent.

Helium, or a similar gas, is used at great depths; cheaper gases, such as nitrogen, can be used in shallow operations. The gas is supplied to the buoyancy chamber from a high pressure reservoir (18) through a control valve (15) and a one-way valve (17). A pump (14) can drive gas from the buoyancy chamber into the reservoir (10) through a further one-way valve (16). The operations of this pump and the control valve (15) are controlled by a differential pressure sensor (13), which monitors the difference between the pressure within (9) and the external pressure, and maintains the former at about 70kPa above the latter. If this difference is greater than the set value, pump (14) is operated to drive gas back into the reservoir; if the difference is too small, gas is allowed to escape into (9) through the valve (15).

The operation of the system is as follows. The device is prepared for a mission by pumping a calculated amount of gas into (18). The amount of gas is such that when the buoyancy chamber (9) has been filled with gas at a pressure corresponding to the operating depth for that mission (i.e. on the bottom, whose depth is known), the pressure of the gas remaining in the reservoir (18) will be slightly above that pressure. If V_C and V_R are the volumes of the chamber and the reservoir respectively, and P_O is the absolute pressure at the operating depth, then the absolute pressure of gas in the reservoir on the surface, P_S, required to give P_O throughout the whole system will be given by: -

$$P_S = P_O(1 + V_C/V_R)$$

This assumes that the processes are isothermal, and the gas behaves as a perfect gas; both of these are reasonable assumptions in the particular circumstances.

Once the device has been set up as described, it is loaded as required and the ballast valve and pump (10) and (11) operated to secure the desired rate of descent. During this descent, gas is admitted into (9) by the control valve (15) under the control of the pressure sensor (5), so that the buoyancy chamber is always under a slight positive pressure. Once the device has reached the bottom, its buoyancy can be varied to the limit of (9) by operating (10) and (11), while the pressure is maintained in the desired band by (15) and (14) under the control of (13). Since the pressures in (9) and (18) are very nearly equal at this stage, relatively little energy is required to compress the gas back into the reservoir.

When the mission has been completed, the buoyancy is adjusted to give the desired rate of ascent, and the device returns to the surface. As the external pressure falls, the pump (14) may not be able to recompress the gas into (18), so the excess escapes through (19). This is of no consequence, since the device can readily be refilled on the surface. Thus, no hoses to the surface are required. Unlike a thruster-driven ROV, which needs a continuous supply of power to maintain itself at a given depth, this device requires power only to change its buoyancy, so that on short missions which do not require many changes of buoyancy, it will be feasible to supply this power from on-board batteries. In this case, only the control signals need to be brought from the surface, for example through an optical fibre cable.

It is clearly desirable to keep the size of the reservoir (18) as small as possible, not only to minimise weight and bulk, but also to make it easier to construct. However, the smaller the reservoir, the more rapidly the pressure will rise within it as gas is pumped in, and so the more energy is required to achieve a given change in buoyancy. The limiting factor is the power available to change buoyancy, coupled with the rate of change of buoyancy required.

It will be seen that this system substitutes tensile stresses in the walls of the reservoir (18) for the compression loads on the pressure-proof pod of a conventional deep buoyancy-control system. This is much more favourable from the point of view of construction, since the risk of buckling is eliminated. This will allow units whose buoyancy can be varied by several tons to be built. Standard steel gas bottles, with a working pressure of 200 Bar can be used down to about 1.5km; at greater depths, high performance materials such as titanium, must be used, but the basic principle is

unchanged. The reservoir (18) can be subdivided if necessary. This allows a modular approach to the design in which the operating depth of a basic unit can be extended by increasing the reservoir with auxiliary storage tanks. The buoyancy chamber (9) can also be sub-divided so that a large system built up from smaller, standard sub-units. Furthermore, if sections of the buoyancy chamber (1) are located in different parts of an ROV, it will be possible to control the trim as well as the total buoyancy by controlling the proportion of the total amount of ballast water in each.

The maximum allowable rate of descent of this device is set by the rate at which gas can be transferred from the reservoir (18) to the buoyancy chamber (9). The latter will be relatively thin-walled, so that it is liable to crush if the pressure within it falls significantly below the external pressure. This problem does not arise during ascent, since excess gas can escape through the over-pressure valve (19). Normally, the rate of descent will be controlled to stay well within the safe range, but the effects of an excessively rapid descent are so potentially disastrous that it is worth providing an emergency back-up system to limit the speed. For example, one method of providing this system involves a "parachute"of strong fabric fixed around the device. This would be folded inwards by the water flow during an ascent, so it would exert little drag. However, the corresponding flow during a descent would spread out the envelope, and the resultant drag, which will increase very sharply with speed, will keep the rate of descent within safe limits for anything less than a gross overload. Being made of fabric, such a device will be light and take up little space.

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CLAIMS

1 A buoyancy control apparatus which includes a gas reservoir whose pressure can be set on the surface to correspond approximately with the ambient pressure at the anticipated operating depth in order to provide a counter-pressure to facilitate changes in buoyancy.

2. A buoyancy control apparatus as in Claim 1, in which changes in buoyancy are achieved by transferring an incompressible liquid between closed but extensible capsules inside and outside the gas reservoir.

3. A buoyancy control apparatus as in Claim 1, in which the gas used to pressurise the reservoir is transferred between the latter and an external chamber.

4. A buoyancy control apparatus as in Claim 3, in which the external chamber has a fixed volume and is provided with means to introduce and expel water to change its buoyancy.

5. A buoyancy control apparatus as in Claim 3 in which the transfer of gas between the reservoir and the external chamber is automatically controlled to maintain the pressure within the latter at or near the external pressure.

6. A buoyancy control apparatus, as in any preceding Claim, in which the buoyancy chamber is provided with an over-pressure valve.

7. A buoyancy control apparatus, as in any preceding Claim, in which the buoyancy chamber is subdivided into several independently controlled sub-chambers, thus allowing the position of the centre of buoyancy, as well as the total buoyancy, to be adjusted.

8. A buoyancy control apparatus, as in any preceding Claim, in which the power to operate the pumps, valves and sensors is provided by on-board batteries.

9. A buoyancy control apparatus, as in any preceding Claim, in which there is provided a means of exerting a drag force during the descent to prevent the speed becoming excessive.